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SYNCHROPHASING OF PROPELLER BLADES OF MULTI-ENGINE AIRCRAFT BY AUTOMATION

By

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The book deals with the problems connected with the analytical determination of the dynamic characteristics of the elements of power installations, methods of making mockups of random stationary disturbances, methods of speeding up engines, etc.

The book is intended for specialists who are working with problems of automatic control of power aviation and rocket units as well as problems in the theory of automatic control.

P R E F A C E

In this compendium there are included articles which deal with different problems in the automatic control of aviation power plants.

In researching the problems of automatic control of power plants the component elements of which consist of heat-exchanging apparatuses much significance must be attached to knowledge of the dynamic characteristics of these apparatuses. In the general system of control the heat-exchanging equipment represents a link described in a two-dimensional space by a system of partial differential equations having variable coefficients. The analytical solution of such a system is bound up with great difficulties. However, with the introduction of a number of permissible simplifications, it proves possible to reduce an original system of equations to definite equations, and in this way determine the approximate transfer function for a heat-exchanging apparatus. This question is dealt with in the article by A. A. Shevyakov and R. V. Takovleva.

For solving the problem as to the worth of one or another system of automatic control of an aircraft power plant, it is necessary to know its behavior under the action of a moving mass of air (wind, air-flow, gusts, turbulent formations in the atmosphere, etc.). Ordinarily the investigation of such a system of automatic control is done with the aid of different mock-up devices; therefore, it is important to get yhe signs which characterize the arbitrary

disturbances of turbulent atmosphere. The article by T. S. Mart'yanova is devoted to a consideration of simple methods of obtaining these signs and their introduction into a mock-up system of automatic control.

The system of automatic control of a modern aviation power plant includes means for regulating the engine and inlet device. In determining the optimum characteristics of such a system of automatic control it is necessary to take into consideration the action on it by the turbulent atmosphere. In the article by V. I. Novikov there is a sufficiently detailed consideration of these questions, and the optimum transmission functions for the elements of control system under discussion are presented.

One of the most complicated problems in systems of automatic control of power plants with turboprop is connected with the starting of the engine. This is explained by the change of all the parameters which characterize in a given moment the mode of the engine's operation during its starting. The introduction of reduced parameters into the system of starting the turbojet enables one to make it more universal. These problems are discussed in the article by Yu. V. Lyuvomudrov.

In connection with the wide development of civilian aviation in all countries, more attention is being paid to the reduction of the noise from the turboprop power plant for multi-engine aircraft. This is attained by means of synchronization of the number of turns and the synchronous phasing of the angles between the blades of the propellers of the separate engines. The article by O. B. Vlasov-Vlasyuk is devoted to a detailed consideration of these questions.

Of decisive significance for any system of control and fuel feed in all aircraft power plants is the dependability of the working of the equipment, but for equipment intended for civilian aviation, t ere is necessary besides this, a great reserve of work in the apparatus. The article by G. P. Anuchkin is devoted to these problems; it is written from materials in foreign periodicals.

When a turboprop airplane lands with the surrounding atmosphere at low temperature, the negative thrust of the engine can reach proportions that are not permissible. For limiting it one may use a device for arresting negative thrust. The results of theoretical research of the dynamics of turboprop control with a negative-thrust-arresting device are discussed in the article by L. N. Getsov and T. S. Mart'yanova.

The correct working of the fuel atomizers has no small effect on the capacity of the aircraft engine for doing work. The article by A. M. Prakhov takes up a number of questions on the working of the atomizers.

SYNCHROPHASING OF PROPELLER BLADES OF MULTI-ENGINE AIRCRAFT BY AUTOMATION

Introduction

Powerplants and, in particular, rotating propellers constitute major sources of noise on aircraft with turboprop engines. According to data of some authors (Bibl. 1), maximum level of noise produced by a rotating propeller at the terminal peripheral speed of propeller blade of 0.9 Mach constitutes roughly 118 db and, at the supersonic terminal peripheral speed - 128 db, which exceeds the noise level produced by turbojet engine.

The level of noise produced by the propeller even with the subsonic peripheral speed exceeds considerably its maximum permissible value.

The sound insulation of aircraft fuselage makes it possible to reduce somewhat the noise level in the passenger cabin, particularly in its h-f range, when is exercises the strongest effect on man's auditory apparatus.

However, the noise due to rotation of propellers, occupying the l-f range, is stronger. Coping with the l-f noise by means of sound insulation of the passenger cabin is not noticeably effective and, therefore, the noise reduction is accomplished by other means, such as decreasing the peripheral speed of propeller blades, increasing the number of propeller blades at relatively low speeds of flight, etc.

Passengers are affected also by a disagrreable action of the sound "beat" produced as a result of the asynchronous rotation of propellers of multi-engine aircraft.

Most disagreeable are beats with frequency range of 0.2 to 8 - 10 cps.

At the beat frequency lower than 0.2 cps, its disagreeable effect is somewhat lesser due to the fact that the power of sound changes at a relatively lower rate. At the beat frequency higher than 10 cps, the human auditory apparatus ceases to perceive differences among rapid changes of sound.

The synchronization of RPM rate of propellers of all engines constitutes a means of coping with "beats" of sound. According to some experimental data (Bibl. 2), the synchronization of RPM rate causes some reduction of the magnitude of total sound; however, this fact is not confirmed by all researches.

As was demonstrated by a number of theoretical and practical investigations, the noise level may differ at the various phase relations among propeller blades, even at the synchronous rotation rates of shafts of all engines. Consequently, we have a minimum noise level at some of these relations. Therefore, a certain decrease in the noise level can be achieved by means of synchrophasing, i. e., maintaining specific values of angular relations among propeller blades of the various engines. The synchrophasing makes it possible to reduce the noise level in the l-f range, that is, in the range where this noise level has the greatest magnitude.

The synchrophasing is expedient also because it diminishes a harmful effect of l-f sound oscillations on aircraft structure, causing the vibration of its individual elements.

The precision in phase maintaining, which insures the constant minimum noise level, amounts to approximately 5 to 7°; it is obvious, however, that it may change in plus or minus for the various structures of aircraft and propellers.

The symphasal rotation of propeller blades of all engines can be achieved in several ways. The first method, theoretically simplest and absolutely reliable,

consists in a rigid connection of engines by means of the joint mechanical shaft. However, the practical realization of this method poses considerable difficulties and causes a substantial increase in aircraft weight.

The synchrophasing through connection of engines by means of the various "flexible shafts", e. g., an electric shaft, also causes a considerable increase in the weight of powerplants of aircraft and, therefore, their application is not expedient. There remains the third method, to wit, maintaining -- with the prescribed degree of accuracy -- the requisite magnitude of phase among propeller blades by acting upon the engine control system and, particularly, on the RPM regulator of propeller shaft (engine shaft). Such an action can be realized only by means of special automatic devices.

The relationship among characteristics of noise produced by rotating propellers, at the asynchronous speed of their rotation and, consequently, at the variable phase among propeller blades of the various engines, was investigates earlier by several authors and is not an object of research in this work. We are presenting in this article the results from investigation of certain possible schemes for synchrophasing of propeller blades by means of automation at the various disturbing actions on the engine in flight. It was assumed during the investigation that the synchrophasing system should satisfy requirements imposed on such a system as regards the accuracy of maintaining the phases only in steady conditions of aircraft flight, inasmuch as the transient conditions of flight (e. g., takeoff and climbing) command only a small part of the entire flight time.

Examination of Possible Structural Schemes of Synchrophasing

In order to select an expedient scheme for synchronizing the blades of propellers of multi-engine aircraft equipped with turboprop engines, we must know the system of automatic control of engines, as well as the requirements which should be satisfied by the synchrophasing system.

When no special devices are available, the angular rotational velocity of propeller shafts of aircraft engines is not the same; this is explained, in the first place, by the impossibility of adjusting with an absolute accuracy each RPM regulator of all engines to one value. Therefore, the difference among RPM rates of the various engines can be relatively great, attaining in certain cases 20% of the nominal value. When the RPM rates of two engines differ by 2%, the nominal RPM rate of propeller shaft being 1000 rpm, one propeller shaft will outstrip the other by 2/3 revolution per second. Consequently, during this time, the blade of propeller having a higher angular rotational velocity will outstrip two and, in some cases, even three blades of propeller revolving with a lower velocity.

The synchronization of RPM rate and the synphasing of propeller blades can be accomplished by two methods, that is, either in one of the engines (driving engine), or by a special master device. The superiority of the first method consists in the reduced amount of equipment; the driving engine may work without a synchrophasing system, thus eliminating the need for a special master device. However, it is known from the practical experience in operation of aircraft with turboprop engines that, even during a steady flight, the engine RPM rate varies constantly with amplitude of $\pm$ 3 to 5 rpm on propeller shaft and mean frequency of about 0.5 cps. Therefore, when the synchrophasing system is switched on, the driving engine will be an additional source of disturbing actions for driven engines; this complicates to a still higher degree the synchrophasing problem, difficult enough as it is.

Because of this fact, one should consider as more expedient the realization of synchrophasing by a spedial master device, provided that its operation is stable.

Fig. 1 shows one of the possible and simplest functional diagrams of synchrophasing. This functional diagram does not include the fuel consumption regulator, performing normally as an open system, and its actions on engine can be regarded as extraneous disturbing actions.

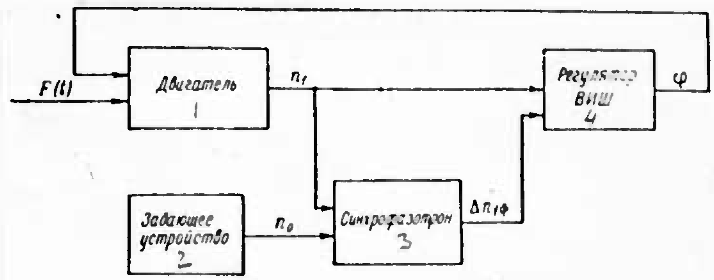


Fig. 1. Functional Diagram of Synchrophasing System.

1 - engine; 2 - master device; 3 - synchrophasotron*; 4 - regulator of variable-pitch prop.

Transl. note: Item 3 in the above diagram reads SINKHROFAZOTRON ("proton-synchrotron" or "synchrophasotron"). The text refers to SINKHROFAZATOR ("synchrophasing unit"), indicating a possible error in the diagram legend.

We shall determine what properties the transfer function of synchrophasing unit should have, in order to fulfill basic conditions determining the fundamental purpose of synchrophasing which consists in the following: upon termination of the transient mode caused by any disturbing actions (including the inaccuracy in adjustment of RPM regulator), the system should establish a constant and quite definite value of the phase.

The system of differential equations describing dynamic properties of the system, whose functional diagram is presented in Fig. 1, has the following form:

Motion equation of compressor:

$$(T_T p+1)\,x_1=-k_{12}\mu_\varphi+k_{13}x_3+F(t); \tag{1}$$

Motion equation of combustion chamber (without allowance for transient delay):

$$x_3=-k_{31}x_1+k_{3q}\mu_q; \tag{2}$$

Motion equation of RPM regulator with variable-pitch propeller:

$$(T_R p+1)\,p\mu_\varphi=k_{21}(x_1+\Delta x_{1\Phi}); \tag{3}$$

We shall write the motion equation of synchrphasing unit in a more general form:

$$\Delta x_{1\Phi}=W_c^0(p)\,x_0. \tag{4}$$

Here $x_1=\Delta n_1/n_{10}$ is the relative deviation of RPM rate;

μ_φ is the relative deviation of the angle of propeller blade setting;

x_3 is the relative deviation of gas temperature before the turbine;

$F(t)$ are the external disturbing actions;

μ_q is the relative change in fuel consumption;

$\Delta x_{1\Phi}$ is the control signal of synchrophasing system, acting upon the adjustment of RPM regulator;

T_T is the time constant of turbocompressor;

T_R is the time constant of RPM regulator with variable-pitch propeller;

k_{12} amplification constant of turbocompressor according to the angle of propeller blade setting;

k_{13} amplification constant of turbocompressor according to the gas temperature before the turbine;

k_{31} amplification constant of combustion chamber according to the RPM rate of turbocompressor;

k_{3q} amplification constant of combustion chamber according to the fuel consumption;

k_{21} amplification constant of RPM regulator;

$W_c^0(p)$ is the transfer function of synchrophasing unit;

χ_θ is the relative deviation of the phase of propeller shaft rotation angle.

The relative deviation of phase is determined within its initial value by the deviation of the engine RPM rate (at the constant rotation rate of master unit).

In fact, let us assume that the RPM rate to which the RPM regulator of driven engine is adjusted exceeds the RPM rate of master unit by the quantity Δn_{1H}. Then we shall have for the rotation angle of propeller shaft of the driven engine

$$\alpha_1 = \frac{1}{p}\frac{\pi n_1}{30} = \frac{1}{p}\frac{\pi n_{10}}{30}(1 + x_1). \quad \text{(a)}$$

Similarly, for the master unit

$$\alpha_0 = \frac{1}{p}\frac{\pi n_0}{30} = \frac{1}{p}\frac{\pi}{30}(n_{10} - \Delta n_{1H}) = \frac{1}{p}\frac{\pi n_{10}}{30}(1 - \Delta x_1), \quad \text{(b)}$$

where

$$\Delta x_1 = \frac{\Delta n_{1H}}{n_{10}}. \quad \text{(c)}$$

The phase mismatch then is

$$\theta = \alpha_1 - \alpha_0 = \frac{1}{p}\frac{\pi n_{10}}{30}(x_1 + \Delta x_1) \quad \text{(d)}$$

or

$$x_\theta = \frac{1}{p}(x_1 + \Delta x_1), \quad (5)$$

where

$$x_\theta = \frac{30}{\pi n_{10}}\theta. \quad \text{(e)}$$

Having substituted the obtained phase expression in the equation of synchrophasing unit (4), and having designated

$$W_c(p) = W_c^0(p)\frac{\pi n_{10}}{30}, \quad (6)$$

we obtain

$$p x_{1\phi} = W_c(p)(x_1 + \Delta x_1). \quad (7)$$

Upon elimination of variable quantities μ_φ; X_3 and $\Delta X_{1\xi}$ from the equation system (1), (2), (3) and (7), we obtain

$$[(T_\tau p+1)(T_R p+1)p^2+k_{12}k_{21}p+k_{12}k_{21}W_c(p)+k_{13}k_{31}(T_R p+1)p^2]\,x_1= \\ =-k_{12}k_{21}W_c(p)\Delta x_1+k_{13}k_{3\mu}(T_R p+1)p^2\mu_q+(T_R p+1)p^2F(t) \tag{f}$$

or, having designated

$$(T_\tau p+1)(T_R p+1)p+k_{12}k_{21}+k_{13}k_{31}(T_R p+1)p=D(p), \tag{g}$$

which includes only the prescribed parameters of engine and RPM regulator with variable-pitch propeller, we shall have

$$[D(p)p+k_{12}k_{21}W_c(p)]\,x_1=-k_{12}k_{21}W_c(p)\Delta x_1+ \\ +k_{13}k_{3\mu}(T_R p+1)p^2\mu_q+(T_R p+1)p^2F(t). \tag{8}$$

In the final analysis, we are interested not in the deviation of RPM rate but in the deviation of phase from the prescribed quantity. Therefore, equation (5) yields

$$x_1=px_0-\Delta x_1 \tag{9}$$

and, having substituted the expression obtained for x_1 in equation (8), we obtain

$$[D(p)p+k_{12}k_{21}W_c p)]\,x_0=D(p)\Delta x_1+k_{13}k_{31}(T_R p+1)p\mu_q+ \\ +(T_R p+1)pF(t). \tag{10}$$

In order to achieve, in steady flight modes, the correspondence of phase to the prescribed quantity at any actions on the engine and with any inaccuracy in adjustment of the RPM regulator, the system must be astatic in relation to signals Δx_1; μ_q and $F(t)$. This can be attained by selection of the corresponding transient function $W_c(p)$.

transfer

Let us consider what requirements must be satisfied by the transfer function $W_c(p)$ for each signal separately.

For the signal on inaccuracy in adjustment of the RPM regulator we have

$$[D(p)p+k_{12}k_{21}W_c(p)]\,x_0=D(p)\Delta x_1. \tag{h}$$

In this case, the system will be astatic in relation to Δx_1, if the transfer function can be represented in form

$$W_c(p)=\frac{W_c'(p)}{p}. \tag{11}$$

Furthermore, it is sufficient for signals μ_q and F(t) that the element having the transfer function $W_c(p)$ be not a differentiator.

Consequently, if one desires the system (10) to be astatic in relation to anyone of actions: ΔX_1, μ_q and F(t), it is necessary and sufficient that the transfer function $W_c(p)$ be reduced to the form of equation (11).

Let us determine conditions of stable performance of the system at $W_c'(p) = k_c$. In this case, the characteristic equation of the entire synchrophasing system will have the following form

$$T_\tau T_R p^5 + [T_\tau + T_R(1 + k_{13}k_{31})]p^4 + (k_{13}k_{31} + 1)p^3 + k_{12}k_{21}p^2 + k_{12}k_{21}k_c = 0. \qquad (12)$$

This system is obviously unstable.

Consequently, the introduction of a synchrophasing unit having the transfer function $W_c(p)$ renders the system unstable.

Let us consider the condition of stability of the synchrophasing system when the transfer function of the synchrophasing unit has the form

$$W_c(p) = \frac{k_1 p + k_2}{p}. \qquad (13)$$

The characteristic equation of the system will then acquire the following form:

$$T_\tau T_R p^5 + [T_\tau + T_R(1 + k_{13}k_{31})]p^4 + (k_{13}k_{31} + 1)p^3 + k_{12}k_{21}p^2 + k_{12}k_{21}k_1 p + k_{12}k_{21}k_2 = 0. \qquad (14)$$

Hence the conditions of stability of the system

$$\left.\begin{aligned} &1)\ [T_\tau + T_R(1 + k_{13}k_{31})](1 + k_{13}k_{31}) - T_\tau T_R k_{12}k_{21} > 0; \\ &2)\ [T_\tau + T_R(1 + k_{13}k_{31})](1 + k_{13}k_{31}) - T_\tau T_R k_{12}k_{21} + \\ &\quad + [T_\tau + T_R(1 + k_{13}k_{31})]\{T_\tau T_R k_2 - [T_\tau + T_R(1 + \\ &\quad + k_{13}k_{31})]k_1\} > 0; \end{aligned}\right| \qquad (15)$$

3) $$[1+k_1-(1+k_{13}k_{31})k_2]\{[T_{\text{т}}+T_R(1+k_{13}k_{31})](1+k_{13}k_{31})-T_{\text{т}}T_Rk_{12}k_{21}\}-T_{\text{т}}T_Rk_{12}k_{21}k_2\{T_{\text{т}}T_Rk_2-[T_{\text{т}}+T_R(1+k_{13}k_{31})]k_1\}>0. \qquad (15)$$

The inequality 1 from equation (15) is always fulfilled, because the control system of engine RPM rate is stable. The fulfillment of conditions 2 and 3 from equation (15) depends on values of parameters k_1 and k_2 of the synchrophasing unit.

Fig. 2 shows the region of stability in coordinates of parameters k_1 and k_2 at the following values of parameters $T_T = 3.6$ sec; $T_k = 0.07$ sec; $k_{12} = 504$; $k_{21} = 0.01$; $k_{13} = 1.46$; $k_{31} = 0.55$; $n_0 = 1075$.

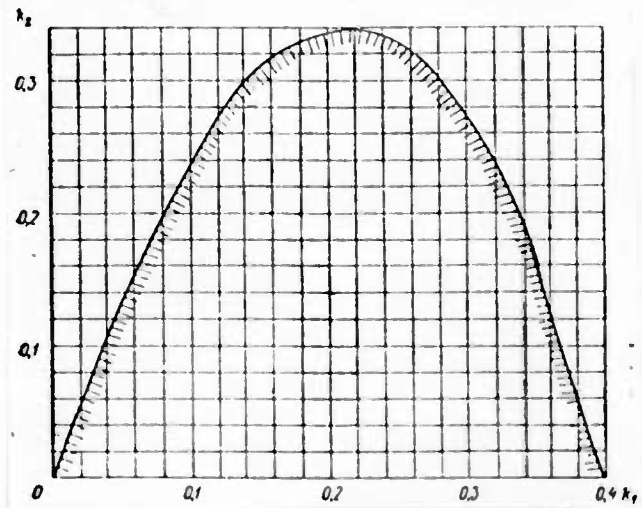


Figure 2. Stability Regions during the Action of Synchrophasing Signal Only.

The transfer function of synchrophasing unit (13) can be realized by two methods. Let us represent the function $W_c(p)$ in form

$$W_c(p) = k_1 + \frac{k_2}{p}. \qquad (1)$$

Hence follows that the re-adjustment of the RPM regulator should be accomplished according to the integral from phase mismatch (fulfilling the condition of astaticity of the system in relation to inaccuracy in adjustment of the RPM regulator), and also according to signal proportional to the phase mismatch (fulfilling the conditions of stability of the system).

In the second method, the action on adjustment of the RPM regulator can be accomplished according to the signal proportional to the difference of RPM rates of propeller shaft and master device, i. e., according to the signal $n_1 - n_0$, inasmuch as

$$p0 = \frac{\pi}{30}(n_1 - n_{10}). \quad \text{(j)}$$

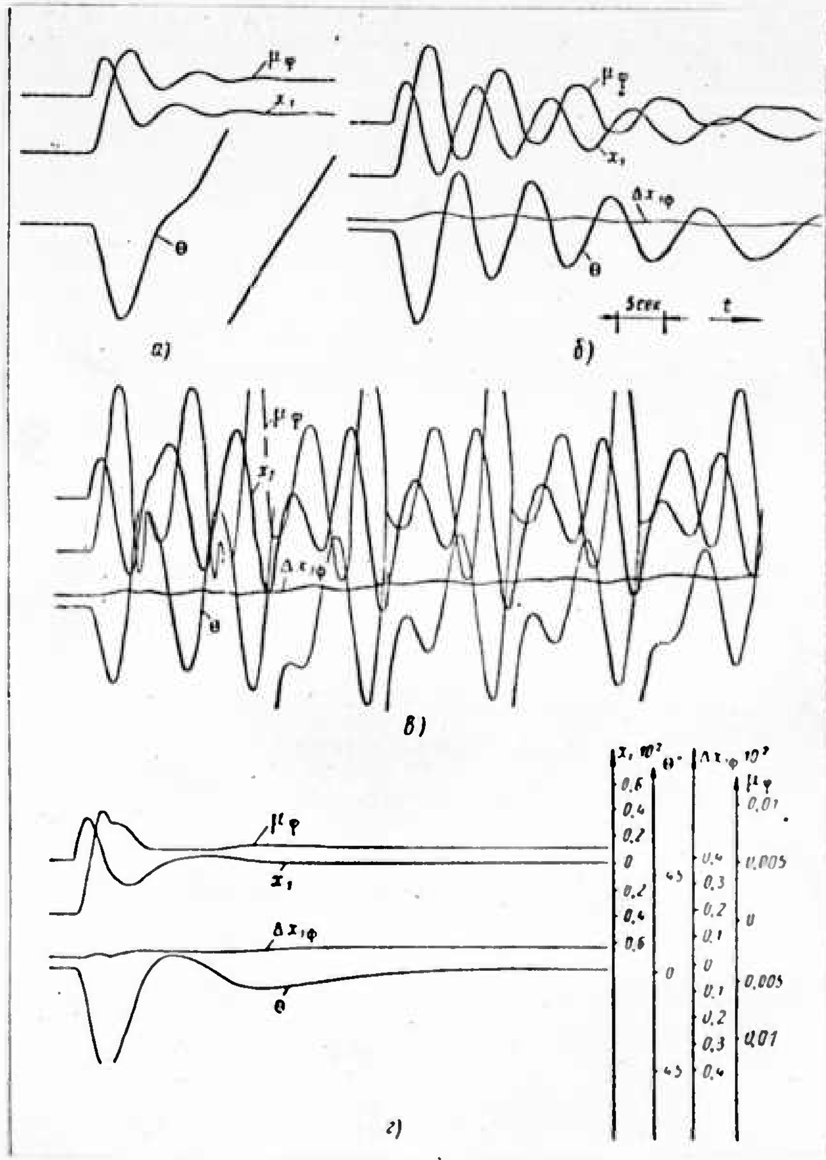
In this case, the equation of synchrophasing unit acquires the form

$$p^2 \Delta x_{1\Phi} = (k_1 p + k_2)(x_1 + \Delta x_1). \quad (16)$$

The problem involved in reduction of the angular rotational velocity of propeller shafts of all engines to one value with the aid of a synchrophasing unit performing only by magnitude of phase mismatch cannot be worked out, because the sign of control signal does not always correspond therein to the required sign of synchronizing signal. This discrepancy is explained by the fact that it does not matter in synchronization of propeller blades which blade of one propeller is set in the given phase with the blade of another propeller; most expedient is the synphasing of nearest blades. In this case, the maximum values of phase deviation may amount to $\pm 360°/2m$, where m is the number of propeller blades. This leads to the following: when the RPM rate of the shaft of propellers being synchronized is difference, the sign of this difference being unchanged, there may occur a change of phase sign; this will cause a change in sign of synchronizing signal, and the system becomes structurally unstable.

The behavior of synchrophasing system under the action only in the signal of phase mismatch Φ, according to the transfer function (13), at the presence

of actions causing maximum deviation of the RPM rate of propeller shaft on the order of 3 - 5 rpm, is shown in Fig. 3.



а) $k_1=k_2=0$, б) $k_1=0.15$, $k=0.0156$, в) $k_1=0.06$, $k_2=0.0156$, г) $k_1=0.03$, $k_2=0.0156$

Fig. 3. Transient Processes of Synchrophasing System.

As can be seen in Fig. 3d, the synchrophasing is accomplished, but the time of phase setting constitutes about 40 sec. At the same time, having compared the oscillogram shown in Fig. 3d with that in Fig. 3a, one can see that the process of synchrophasing is determined mainly by the quality of performance of the RPM regulator. because amplification coefficients in channels of RPM rate synchronization and synchrophasing have a small value, and the synchrophasing unit accomplishes merely the function of reducing the phase to the required value at the end of transient process.

An increase in these coefficients causes either longer oscillatory processes or self-scillations (due to the effect of non-response zone of the regulator) with deviation of the average value of RPM rate from the synchronous one, which excludes the establishment of a constant phase value. Particularly disadvantageous is the increase of amplification coefficient in phase integral channel.

More favorable transient processes can be obtained by the second method of realization of the transfer function (13), which can be seen in Fig. 4.

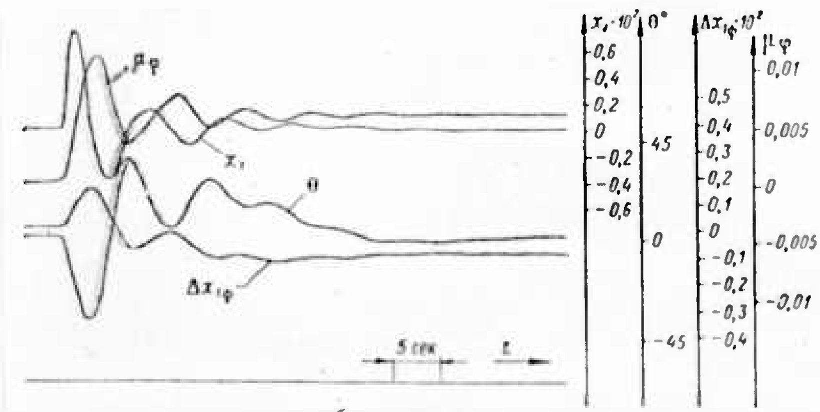


Fig. 4. Transient Processes with Synchrophasing Unit Being Acted Upon by Signals of Difference in RPM Rate and Phase Difference.

However, in this case, the character of transient process is determined mainly by the quality of performance of the RPM regulator.

We have considered above synchrophasing processes for an ideal synchrophasing unit.

If each channel of synchrophasing unit contains an aperiodic element, its dynamic properties are described by the system of differential equations in form

$$\left.\begin{aligned}(T_c p+1)\Delta x_c &= k_1(x_1+\Delta x_1);\\ (T_\Phi p+1)p\Delta x_\Phi &= k_2(x_1+\Delta x_1);\\ p\Delta x_{1\Phi} &= \Delta x_c+\Delta x_\Phi.\end{aligned}\right\} \quad (17)$$

Stability regions, corresponding to this case at $T_c = T_\Phi = T$, are shown in Fig. 5. As can be seen in this figure, an increase in the value of time constant of the aperiodic element in circuits of the synchrophasing unit does not cause any great changes in the stability region at small values of T.

The functional diagram of synchrophasing system with the synchrophasing unit described by differential equations (17) is shown in Fig. 6, where

$$x_{s_1} = \frac{\alpha_1 \cdot 30}{\pi n_{10}}, \quad x_{s_0} = \frac{\alpha_0 \cdot 30}{\pi n_0} \quad (k)$$

are the relative values of rotation angle of propeller shafts and master unit, respectively. Transient processes in this system at $T_c = T_\Phi = T$ are shown in Fig. 7. As can be seen in this figure, the character of transient processes in the initial sections does not differ substantially from transient processes obtained at the absence of inertness of the synchrophasing unit.

(see following page for Figure 5)

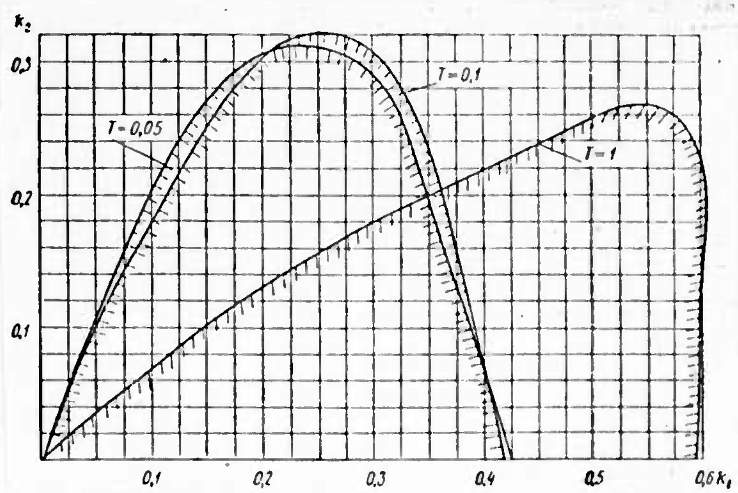


Figure 5. Stability Regions of Synchrophasing System with Inertial Synchrophasing Unit.

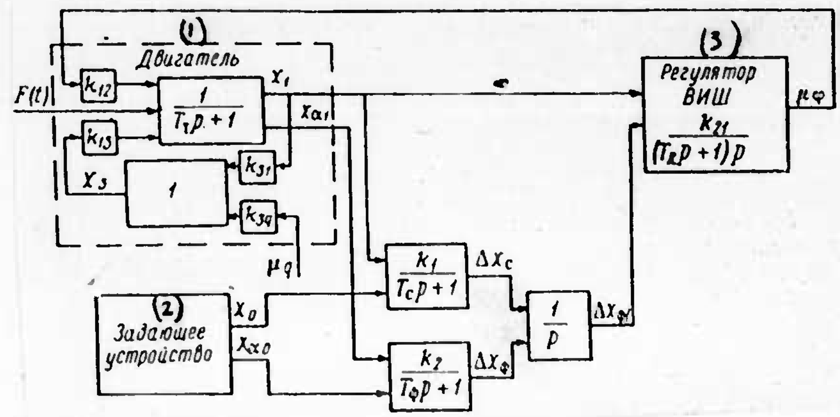


Fig. 6. Functional Diagram of Synchrophasing System with Inertial Synchrophasing Unit.

1 - engine; 2 - master unitl 3 - regulator of variable-pitch propeller.

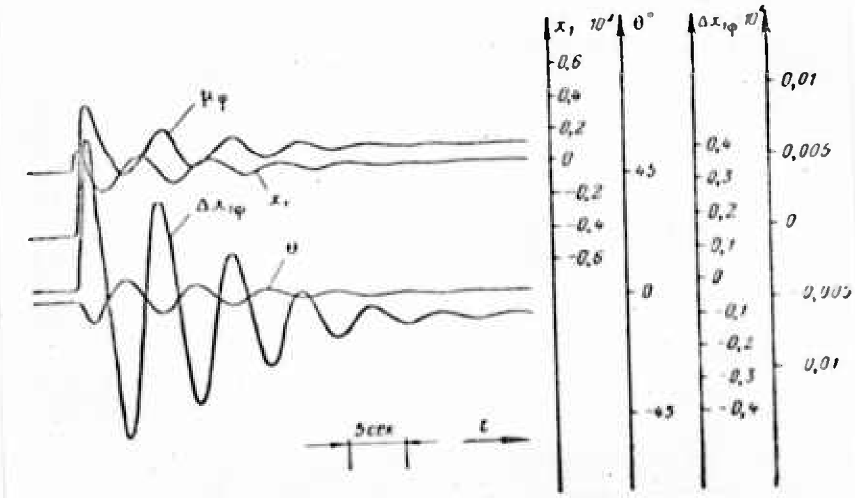


Fig. 7. Transient Processes of Synchrophasing System with Inertial Synchrophasing Unit.

Strict requirements concerning the phase maintenance accuracy at the presence -- during a stabilized flight -- of constantly acting, disturbing effects, causing the deviation of RPM rate of propeller shaft by the value $\pm 3 - 5$ rpm, obviously cannot be met without improvement in quality of control of the RPM rate of engine shaft.

As demonstrated by the analysis presented above, the latter cannot be achieved even with the ideal synchrophasing unit. At the real magnitude of disturbing action, the phase changes within a wide range and, at the first moment, there occurs even a change in phase sign.

The synchrophasing process cannot be improved also by introducing the correcting devices into the circuit of synchrophasing unit. In fact, if the correcting device is inserted into the synchrophasing channel of synchrophasing unit in form of an ideal differentiator, the motion equation of synchrophasing unit will be

$$p^2\Delta x_{1\phi} = [k_1 p + k_2(\tau_\phi p + 1)](x_1 + \Delta x_1) \quad (1)$$

or, upon transformations,

$$p^2\Delta x_{1\phi} = [(k_1 + k_2\tau_\phi)p + k_2](x_1 + \Delta x_1). \quad (18)$$

Hence it is clear that the introduction of the differentiator into the synphasing channel does not cause any changes, because the expression of coefficient $k_1 + k_2\tau_\phi$ at the operator in the first power in the right section of equation can be considered as k_1' and equation (18) changes into the initial equation (16).

If a parallel correcting device, that is, the ideal differentiator, is inserted into the RPM synchronization circuit, the equation of synchrophasing unit will assume the form

$$p^2\Delta x_{1\phi} = [k_1(\tau_c p + 1)p + k_2](x_1 + \Delta x_1). \quad (19)$$

The characteristic equation of the system will be then

$$\begin{gathered} T_\tau T_R p^5 + [T_\tau + T_R(1 + k_{13}k_{31})]p^4 + (1 + k_{13}k_{31})p^3 + \\ + k_{12}k_{21}(1 + k_1\tau_c)p^2 + k_{12}k_{21}(k_1 p + k_2) = 0. \end{gathered} \tag{m}$$

Let us determine hence expressions of k_1 and k_2 for construction of the stability region by the method of D-division

$$\left.\begin{aligned} k_1 &= \frac{1 + k_{13}k_{31} - T_\tau T_R\omega^2}{k_{12}k_{21}}\,\omega^2; \\ k_2 &= \frac{k_{12}k_{21}(k_1\tau_c + 1) - [T_\tau + T_R(1 + k_{13}k_{31})]\,\omega^2}{k_{12}k_{21}}\,\omega^2. \end{aligned}\right\} \tag{20}$$

Having excluded ω, we obtain

$$k_2 = k_{12}k_{21}\left\{\left[\tau_c - \frac{1 + k_{13}k_{31}}{T_\tau T_R}(k_{13}k_{31}T_R + T_\tau + T_R)\right]k_1 + 1\right\}k_1. \tag{n}$$

Hence the maximum value of k_1 ($k_2 = 0$) is equal to

$$k_1 = \frac{1}{\frac{1 + k_{13}k_{31}}{T_\tau T_R}[T_R(1 + k_{13}k_{31}) + T_\tau] - \tau_c} \tag{o}$$

and the maximum value of k_2:

$$k_2 = k_{12}k_{21}\frac{1}{\frac{1 + k_{13}k_{31}}{T_\tau T_R}(T_R(1 + k_{13}k_{31}) + T_\tau] - \tau_c}. \tag{p}$$

It is clear from these expressions that increasing the value of τ_c causes an increase in amplification coefficients of the synchrophasing unit, k_1 and k_2, and, consequently, an expansion of the stability region.

However, an introduction of such a correcting device into the synchronization circuit of RPM rate of the synchrophasing unit is equivalent to increasing the amplification coefficient in the circuit of RPM regulator.

In fact, equality (19) can be presented in the following form (on assumption that, as a result of operation of the synchrophasing unit, the re-adjustment of the RPM regulator to the required value has been accomplished and $\Delta\chi_1 = 0$).

$$\Delta x_{1\phi} = \left[k_1\tau_c + \frac{1}{p^2}(k_1 p + k_2)\right]\bar{x}_1 \tag{q}$$

and the equation of RPM regulator will assume the form

$$(T_R p+1)\,p\mu_\varphi=\left[k_{21}(1+k_1\tau_c)+\frac{k_{21}}{p^2}(k_1 p+k_2)\right]x_1. \qquad \text{(r)}$$

It is not permissible to increase the amplification coefficient in the circuit of the RPM regulator, because this coefficient is selected normally from conditions of obtaining satisfactory processes of RPM regulation and is a definite quantity.

Basing on the analysis conducted above, one can conclude that the process of synchrophasing cannot be improved by introducing into the circuit of synchrophasing unit the correcting devices in form of differentiators. The synchrophasing processes can be improved only by improving the engine control system, i. e., by introduction of stabilizing devices into the circuit of the RPM regulator.

We can consider two kinds of stabilizing signals in the engine control system:

a) introduction of signal proportional to the rate of RPM change into the circuit of RPM regulator of the propeller shaft (introduction of accelerometer);

b) stabilization of control system by acting upon fuel consumption by the RPM rate mismatch signal.

In the first case, the differential equation describing the motion of RPM regulator assumes the following form (for the real accelerometer):

$$(T_R p+1)\,p x_2=k_{21}\left[\left(\frac{\tau_a p}{T_a p+1}+1\right)x_1+\Delta x_{1\Phi}\right]. \qquad (21)$$

The characteristic equation of the closed system of synchrophasing will be in this case

$$\begin{aligned} &T_\tau T_R T_a p^6+[T_R T_a(1+k_{13}k_{31})+T_\tau(T_R+T_a)]\,p^5+\\ &+[T_\tau+(T_R+T_a)(1+k_{13}k_{31})]\,p^4+[1+k_{13}k_{31}+k_{12}k_{21}(T_a+\tau_a)]\,p^3+\\ &+k_{12}k_{21}(1+k_1 T_a)p^2+k_{12}k_{21}(k_1+T_a k_2)p+k_{12}k_{21}k_2=0. \end{aligned} \qquad \text{(s)}$$

Hence the expressions for k_1 and k_2 in construction of the stability region by the method of D-division will be

$$k_1 = \frac{1 + k_{13}k_{31} + k_{12}k_{21}\tau_a - [T_\tau T_R - T_a^2(1 + k_{13}k_{31})]\,\omega^2 - T_\tau T_R T_a^2\,\omega^4}{k_{12}k_{21}(1 + T_a^2\omega^2)}\,\omega^2;$$

$$k_2 = \frac{k_{12}k_{21} - [T_\tau + T_R(1 + k_{13}k_{31}) - k_{12}k_{21}T_a(T_a + \tau_a)]\,\omega^2 - T_a^2[T_\tau + T_R(1 + k_{13}k_{31})]\,\omega^4}{k_{12}k_{21}(1 + T_a^2\omega^2)}\,\omega^2. \qquad (t)$$

These expressions for k_1 and k_2 can be represented in the following form:

$$k_1 = \frac{\tau_a}{1 + T_a^2\omega^2}\,\omega^2 + \frac{1 + k_{13}k_{31} - T_\tau T_R\omega^2}{k_{12}k_{21}}\,\omega^2;$$

$$k_2 = \frac{T_a\tau_a}{1 + T_a^2\omega^2}\,\omega^4 + \frac{k_{12}k_2 - [T_\tau + T_R(1 + k_{13}k_{31})]\,\omega^2}{k_{12}k_{21}}\,\omega^2. \qquad (u)$$

Hence it is clear that coefficients K_1 and k_2 are two components constituting frequency functions. At the same time, constants introduced into the first components depend only on parameters of the accelerometer, and second ones on parameters of engine and variable-pitch propeller regulator (without accelerometer).

Let us introduce the designation $\frac{\tau_a}{T_a} = l$. The expressions of coefficients k_1 and k_2 will then assume the following form:

$$\left.\begin{aligned} k_1 &= \frac{lT_a}{1 + T_a^2\omega^2}\,\omega^2 + \frac{1 + k_{13}k_{31} - T_\tau T_R\omega^2}{k_{12}k_{21}}\,\omega^2;\\ k_2 &= \frac{lT_a^2}{1 + T_a^2\omega^2}\,\omega^4 + \frac{k_{12}k_{21} - [T_R(1 + k_{13}k_{31}) + T_\tau]\,\omega^2}{k_{12}k_{21}}\,\omega^2. \end{aligned}\right\} \qquad (22)$$

One can see from expressions obtained for k_1 and k_2 that the introduction of the accelerometer causes an expansion of the stability region and an increase in amplification coefficients of the synchrophasing unit.

Apart from that, the stability region decreases with increasing T_a at the constant value of formula $l = \frac{\tau_a}{T_a}$ and increases at the constant value of T_a and with an increase in formula $l = \frac{\tau_a}{T_a}$.

Fig. 8 shows stability regions of the synchrophasing system for $l = 10$ at the various

values of T_a and with above-indicated parameters of the engine and variable-pitch propeller regulator.

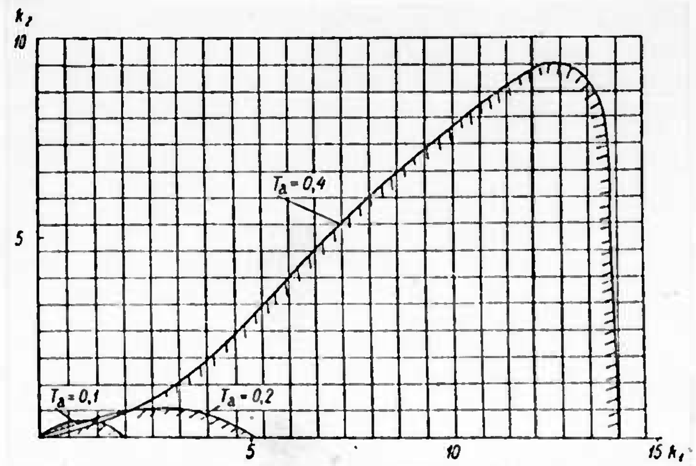


Fig. 8. Regions of Synchrophasing System on Introduction of Accelerometer into RPM Control Circuit.

Fig. 9 shows transient processes in the synchrophasing system at the action in form of a single step function. It can be seen in this figure that the introduction of the accelerometer causes a substantial improvement in the synchrophasing process at a relatively small phase deviation.

Improvement in the quality of the process of controlling the number of revolutions of a turboprop can be attained through the introduction of additional action in the consumption of fuel on a signal of deviation in the number of revolutions between the master device and the dependent engine. The structure of such a system is shown in Fig. 10.

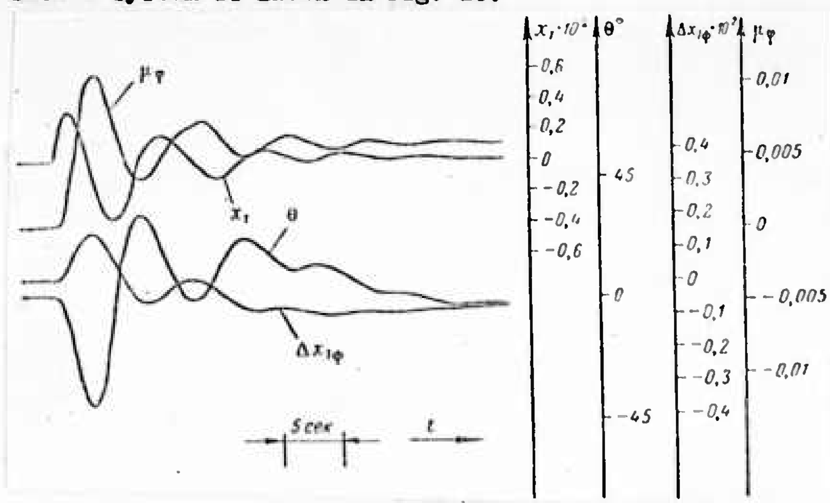


Fig. 9. Transition processes of the system of synchronization in the introduction of an accelerometer into the chain of control of the number of revolutions.

The system of differential equations for this case has the following form:

equation of motion of the turbocompressor

$$(T_T p + 1) x_1 = -k_{12}\mu_\varphi + k_{13} x_3 + F(t); \qquad \text{(aa)}$$

equation of the motion of the combustion chamber (not taking into account the transmission delay)

$$x_3 = -k_{31} x_1 + k_{3q}\mu_q - k_T (x_1 + \Delta x_1); \qquad \text{(bb)}$$

equation of the motion of the regulator of the number of revolutions with controllable-pitch propeller

$$(T_R p + 1) p\mu_\varphi = k_{21} (x_1 + \Delta x_{1\phi}); \qquad \text{(cc)}$$

equation of the motion of the phase synchronizer

$$p^2 \Delta x_{1\phi} = (k_1 p + k_2)(x_1 + \Delta x_1). \qquad \text{(dd)}$$

Let us unite the equations of the turbocompressor and the combustion chamber after having excluded $\underline{x_3}$:

$$(T_т + 1 + k_{13}k_{31} + k_{13}k_т)\,x_1 = -k_{12}\mu_\varphi + k_{13}k_{3q}\mu_q - k_{13}k_т\Delta x_1 + F(t). \qquad \text{(ee)}$$

From the relationship obtained it is seen that the introduction of the action on the consumption of fuel is equivalent to an increase in the automatic speed regulation of the engine, which makes it possible to increase the coefficient of amplification in the chain of the regulator of the number of revolutions, and in this way improve the process of regulating the number of revolutions, and, consequently, also the synchronozation. However, the increase

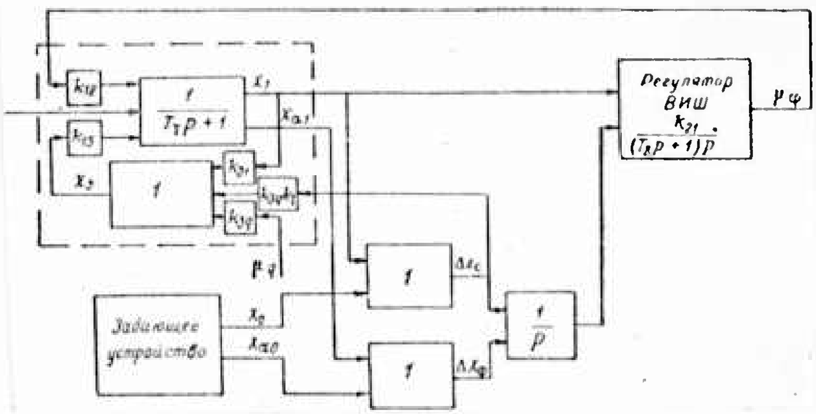


Fig. 10. Diagram of the circuit of the synchronization circuit in the introduction of the stabilizaing signal through on the consumption of fuel on deviation in the number of revolutions between the dependent engine and the master device

in the coefficiet of amplification of the regulator of the number of revolutions can be accomplished only in the case where a phase synchronizer is included in in all modes of operation of the engine, which does not correspond to requirements. Besides, this is connected with change in the parameters of the regulator of the number of revolutions, and therefore it is not good in the case of the setup of a phase-synchronization system on aircraft in actual operation.

In this connection it is more feasible not to have an increase in the coefficient of amplification of the regulator of the number of revolutions, and to introduce an equivalent signal proportional to the rate of deviation of the number of revolutions in the chain of the phase synchronizer along the channel of synchronization of the number of revolutions.

In Fig. 11 there are shown the transition processes in the system of synchronization corresponding to the design scheme presented in Fig. 10. From this layout it is seen that with a greater coefficient of amplification in the chain of action on the consumption of fuel there occur automatic oscillations with a comparatively small amountof deviation in the phase difference (Fig. 11, a). Decrease in the coefficient of amplification in the chain of action on the fuel consumption leads to a slow extinguishing of the oscillation process with an increase in the deviation of the value for the difference of phase (Fig. 11, b)

Then introduction of a real differentiating link into the channel of synchronization of the number of revolutions leads to considerable improvement in the transition processes in the number of revolutions and phase difference (Fig. 11, c). However, the signal of the readjustment of the regulator of the number of revolutions is much stronger in this case.

Investigation of the System of Phase Synchronization in Random Effects

In flight the engine is subjected to the effect of external disturbances which cause a change in the number of revolutions of the shaft within certain limits. In this case with an established regime of flight the number of revolutions of the propeller shaft fluctuates with a frequency of about 0.5 cps and amplitude of 2--5 rpm on the propeller shaft. Therefore one is interested in the research of process of phase synchronization with that kind of action on the engine.

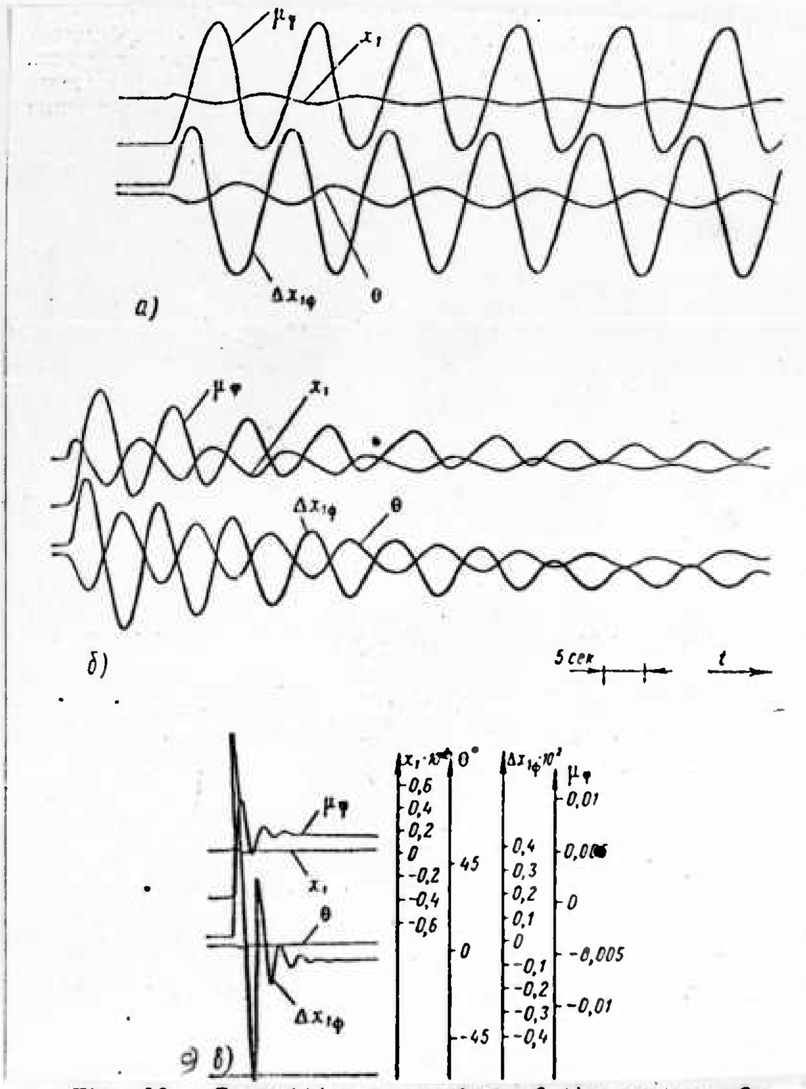


Fig. 11. Transition processes of the system of phase synchronization by action on the fuel consumption

a) $k_1=4$, $k_2=0.076$, $k_T=10$; b) $k_1=1$, $k_2=0.026$, $k_T=1$; c) $k_1=3$, $k_2=0.026$, $\tau_a=4$ sec., $T_a=0.04$ sec, $k_T=10$.

The research of the process of phase synchronization is accomplished on

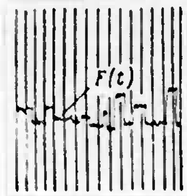


Fig. 12. Form of the signal on the output of the generator of random effects

the electron simulating unit with the use of a specially developed signal generator which imitates the turbulence of the atmosphere which causes a fluctuation in the rpm of the engine.

In this case for the purpose of simplifying the circuit of the generator and increasing the dependability of its working, there was allowed some deviation from the character of real disturbing effects. If under real conditions the rate of change in the disturbing effect always has a finite value, then the signal on the output of the generator changed by a jump (Fig. 12). For approximating the conditions

of the working of the system of the phase synchronizer on the model, to the real conditions, the frequency and the amplitude of the disturbing effects are selected in such a way that the character of the change in the model which characterizes the deviation in the number of revolutions will be analogous to the vehavior of the rpm of the engine in an established flight regime.

In Fig. 13 there is presented the circuit of the simulation of the system of synchronization.

A peculiarity of the simulation of the system of phase synchronization is the necessity of obtaining on the model a signal which is proportional to the phase difference. Clearly, with a relatively large deviation in the rpm of the engine from the rpm of the master device in the transition regime some shifts of phases may occur. If the rpm of the dependent engine shifts from that of the master by some value, and this deviation is preserved, then the sign of phase difference will periodically change with the period $\frac{60\ m}{n_1}$ sec., where n_1 is the rpm of the engine.

For realizing the possibility of obtaining on the model as signal which is proportional to the phase difference under any probable deviations in the rpm of the dependent engine from the synchronous ones, one can use the circuit shown in Fig. 14, which works in the following fashion.

A voltage which is proportional to the difference of the rpm of the engine shaft from that of the transmitter is fed onto one of the contacts of the connecting group P_{11} relay P_1. On to the second contact of the same group this same voltage is supplied, but with the reverse sign, and this is accomplished by connecting in an inverter (operational amplifier 1). Voltage taken from the middle point of this group is fed to the input of the integrating unit 2, on the output of which one gets the voltage proportional to the absolute value of the phase difference.

When a voltage is obtained on the output of unit 2 which corresponds to the

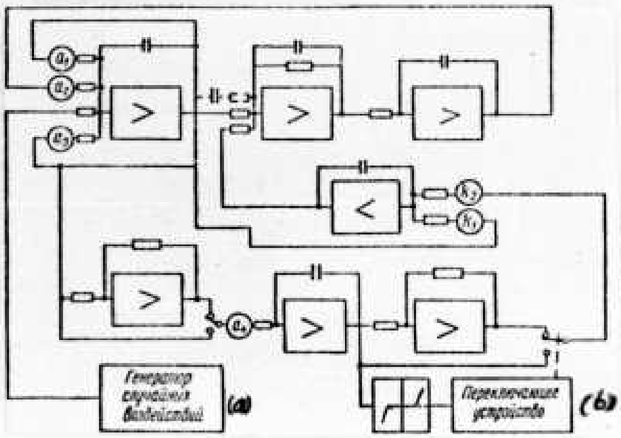


Fig. 13. Circuit of simulation of the system of phase synchronization under random effects
(a) generator of random effects
(b) switchover device

the phase difference at which there should be a shift of the sign, a polarized rely cuts in on the circuit of relay P_2 which causes the dropout of relay P_1, and, consequently, to the change in the sign of the signal on the input of the integrating unit 2.

Simultaneously with this action there occurs the switchover of the contacts of the contact group P_{12} onto a certain contact which passes the signal with the reverse sign. On the armature of this contact group a signal is received which is proportional to the phase difference.

In Fig. 15 there is shown the process of maintaining the phases under random effects in the absence of stabilizing signals in the phase-synchronization system. As is seen from this graph the phase changes over the whole range of its possible deviations, and consequently

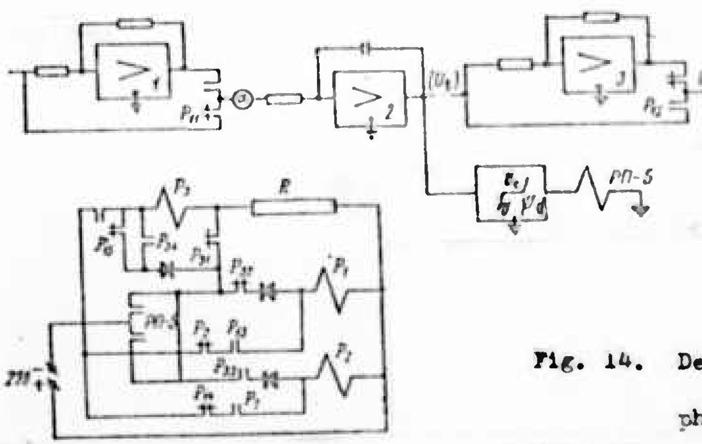


Fig. 14. Device for ob- phase signal

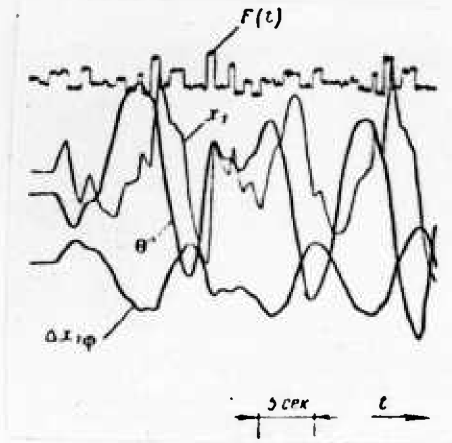


Fig. 15. Transition processes of the phase-synchronization system during random effects and absence of stabilizing signals, $k_1 = 0.2$ and $k_2 = 0.026$

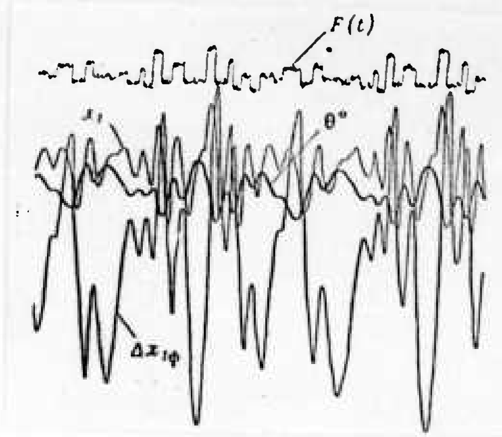


Fig. 16. Transition processes of the phase-synchronization system during random effects with accelerometer in the rpm-control circuit (k_1=3, k_2=0.078, T_a=0.35, and τ_a=3.5)

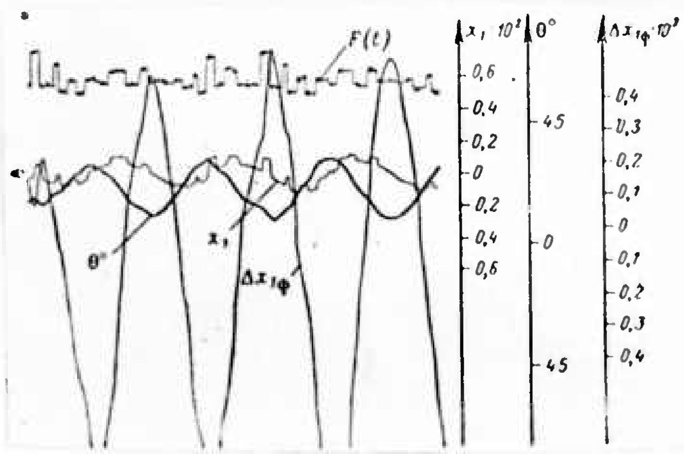


Fig. 17. Transition processes in the phase-synchronization system during random effects and stabilization signal through action of the fuel consumption, $k_1 = 4$, $k_2 = 0.078$, and $k_T = 10$.

the required precision of phase maintenance is not sustained. The introduction

of the accelerometer into the circuit of the rpm regulator enables one to improve considerably the process of phase synchronization (Fig. 16)

The process of phase synchronization is also improved by the introduction of a stabilizing signal through action on the consumption of fuel (Fig. 17).

The introduction into the circuit of a phase-synchronization signal proportional to the rate of deviation of the rpm improves considerably the process of synchronization even during random effects (Fig. 18).

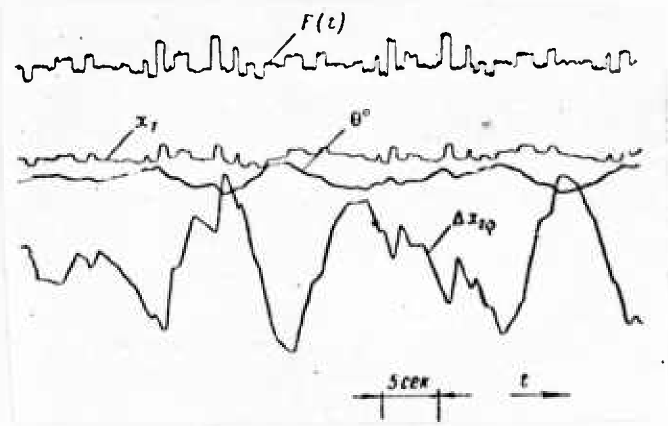


Fig. 18. Transition processes of the phase-synchronization system during random effects and stabilization signals through action on the fuel consumption and in accordance with the rate of deviation of the rpm in the synchronization circuit ($k_1=3$, $k_2=0.026$, $k_T=10$, $T_a=0.4$, and $\tau_a=4$).

C o n c l u s i o n s

1. For most of the known systems of rpm control for the turboprop engine, the introduction of a system of phase synchronization, astatic with relation to external disturbing action, change in the consumption of fuel and inaccuracy of adjustment, it is essential that the phase synchronizer have a transmission function reducible to the formula

$$W_c(p) = \frac{W'_c(p)}{p}$$

2. The requirements applicable to the process of phase synchronization--maintaining the phases within narrow permissible limits--can be satisfied only

in the case where there is introduced into these devices stabilizing signals (accelerometer into the rpm regulator or action on the consumption of fuel in accordance with a signal of the deviation in rpm).

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